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by

Zhou Zhulin

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THE HIGH-FREQUENCY DIELECTRIC PROPERTIES OF GLASS FIBRE REINFORCED PLASTIC AND HONEYCOMB LAYERS[1]

Zhou Zhulin

Shanghai Glass Fibre Reinforced Plastic Institute

The dielectric constant and the dielectric loss angle tangent of glass fibre reinforced plastic are both relatively small; it is a good wave-penetration material. To investigate these properties further and reduce the experimentation time, in order to obtain the best calculations concerning the wave-penetration rate of honeycomb layer structure, it is necessary to undertake a theoretical investigation of the properties and discover formulas with a practical value. This paper introduces the work we have done in this area.

1. The High-Frequency Dielectric Properties of Glass Fibre Reinforced Plastic

The dielectric properties of glass fibre reinforced plastic have a close relationship with the dielectric properties of the raw materials. The dielectric properties of several of these materials are shown in Table 1 [1,2].

Normally, non-polar polymers (like polyethelene and polystyrene) have rather low dielectric property figures, with ε between 2 and 2.4 and $tg\delta$ below 0.0003.

The dielectric property figures for glass become smaller as the alkali content is reduced. For this reason, alkali-free glass fibre with low alkali contents is normally used.

1. Zhong Tianlin and Wei Junnan participated in the experimental work.

Table 1. Dielectric Properties of Some Raw Materials

(1) 性能 / (2) 频率 / 材料 (3)	密度 (4) (kg/m³)	ε		tgδ	
		10^6Hz	9.375×10^9Hz	10^6Hz	9.375×10^9Hz
E玻璃 (5)	2540		6.13		0.0039
S玻璃 (6)	2490		5.21		0.0068
D玻璃 (7)	2160		4.00		0.0026
石英 (8)	2200		3.78		0.0002
酚醛树脂 (9)	1250—1300	4.5—5.0		0.015—0.030	
环氧树脂 (10)	1200—1220	3.5—5.0	2.78	0.010—0.019	0.012
酚醛改性环氧 (11)	1160—1210	3.4		0.024	
饱和聚酯 (12)	1310—1380	3.1—3.3		0.0022—0.030	
不饱和聚酯 (13)	1100—1460	2.8—4.1	2.78*	0.006—0.026	0.005*
有机硅树脂 (14)	1260	2.9—5.0		0.003—0.050	

*Non-solidified polyester.

Key: (1) Property; (2) Frequency; (3) Material; (4) Density; (5) E glass; (6) S glass; (7) D glass; (8) Quartz; (9) Phenolic resin; (10) Epoxy resin; (11) Phenolic aldehyde modified epoxy; (12) Saturated polyester; (13) Unsaturated polyester; (14) Organic silicon resin.

1.1. Dielectric Constant of Glass Fibre Reinforced Plastic

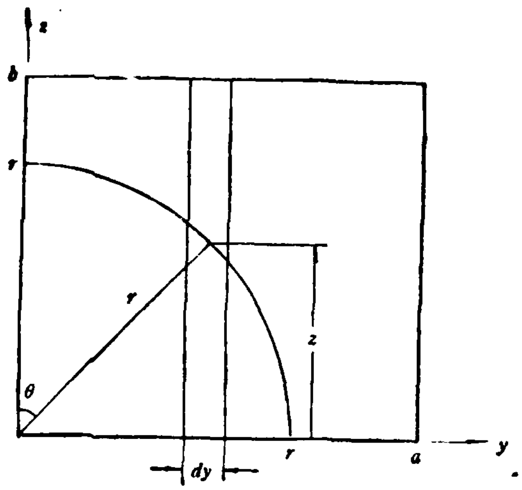
The dielectric constant for glass fibre reinforced plastic, like the mechanics properties [3-5], may be calculated theoretically on the basis of the properties of the raw materials, classed by group, and the group class ratio.

For the dielectric constant in the direction of the fibres, the fibres and the resin may be regarded as composite capacitors in parallel connection [6]; the dielectric constant in the direction of the fibres for unidirectional glass fibre reinforced plastic may be obtained with the following formula:

$$\varepsilon_{\parallel} = V_f \varepsilon_f + (1 - V_f - V_0)\varepsilon_m + V_0 \varepsilon_0 \qquad (1)$$

In the formula, f-subscript represents the fibre, m-subscript the resin, and V_0 the interval rate.

When solving for the dielectric constant in the direction of the vertical fibres, we may first assume that the fibres are arranged at right angles, and select a one-quarter unit form as shown in Fig. 1, and then, using the concept of series-connected and parallel connected capacitors and integration, solve for the upper and lower limits of the crosswise dielectric constant as follows:



$$\left(r = \sqrt{\frac{4V_f}{\pi}}\right)$$

Fig. 1. Calculation model.

$$\varepsilon'_\perp = \{\varepsilon_m\} \Big/ \left\{ \frac{b-r}{b} + \frac{\varepsilon_m}{b(\varepsilon_f - \varepsilon_m)} \times \left[\frac{a\pi}{2} - \frac{2a^2\varepsilon_m}{\sqrt{a^2\varepsilon_m^2 - (\varepsilon_f - \varepsilon_m)^2 r^2}} \mathrm{tg}^{-1} \times \sqrt{\frac{a\varepsilon_m - (\varepsilon_f - \varepsilon_m) r}{a\varepsilon_m + (\varepsilon_f - \varepsilon_m) r}} \right] \right\},$$

$$\varepsilon''_\perp = \left[\frac{a-r}{a} - \frac{b\pi\varepsilon_f}{2a(\varepsilon_f - \varepsilon_m)} + \left(\frac{b\varepsilon_f}{\varepsilon_f - \varepsilon_m} \right)^2 \times \frac{2(\varepsilon_f - \varepsilon_m)}{a\sqrt{b^2\varepsilon_f^2 - (\varepsilon_f - \varepsilon_m)^2 r^2}} \mathrm{tg}^{-1} \times \sqrt{\frac{b\varepsilon_f + (\varepsilon_f - \varepsilon_m) r}{b\varepsilon_f - (\varepsilon_f - \varepsilon_m) r}} \right] \varepsilon_m. \quad (2)$$

The crosswise dielectric constant $\varepsilon_\perp$ is the average of $\varepsilon'_\perp$ and $\varepsilon''_\perp$, or

$$\varepsilon_\perp = (\varepsilon'_\perp + \varepsilon''_\perp)/2. \quad (3)$$

For bidirectional glass fibre reinforced plastic, the theoretical formulas for calculating the dielectric constant along the warp and the weft are as follows:

$$\varepsilon_L = \frac{n_L}{n_L + n_T}\varepsilon_f + \frac{n_T}{n_L + n_T}\varepsilon_\perp, \quad (4)$$

$$\varepsilon_T = \frac{n_L}{n_L + n_T}\varepsilon_\perp + \frac{n_T}{n_L + n_T}\varepsilon_f, \quad (5)$$

In the formulas, m_L and m_T represent the ratio of warp and weft fibres, respectively.

The crosswise dielectric constant for glass fibre reinforced plastic is related to the fibre content as shown in Fig. 2. Figure 2 shows the calculated results of the estimation formula in references [1] and [5],

$$\log \varepsilon = V_f \log \varepsilon_f + (1 - V_f) \log \varepsilon_m \qquad (6)$$

and of the experimenal formula in reference [7],

$$\varepsilon = 5.45 - 0.03A \qquad (7)$$

For calculations, ε_f=6.13 and ε_m=3.5.

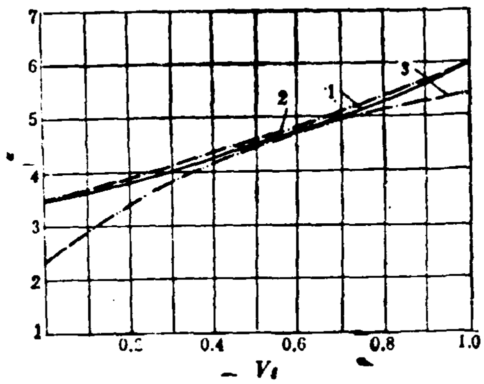


Fig. 2. Relation of crosswise dielectric constant and fibre content.
1. Formula (3); 2. Formula (6); 3. Formula (7).

A comparison between the experimental and theoretical values for dielectric constants for some glass fibre reinforced plastics is shown in Table 2.

Table 2. Comparison of Experimental and Theoretical Dielectric Constants for Glass Fibre Reinforced Plastics

(2) 材料 / 性能 (1)		(3) DAP 玻璃钢	(4) 酚醛-环氧玻璃钢	(5) 聚酯玻璃钢
(6) 树脂含量 A(%)		48	30	50
(7) 介电常数 ε	(8) 测试值	4.30	4.5—4.7	4.25—4.50
	(9) 理论值	4.25	4.6	4.15—4.[illegible]0
	(10) 误差(%)	1.2	−2.1—2.2	−2.2—2.3

Key: (1) Property; (2) Material; (3) DAP glass fibre reinforced plastic; (4) Phenolic/epoxy glass fibre reinforced plastic; (5) Polyester glass fibre reinforced plastic; (6) Resin content A, %; (7) Dielectric constant ε; (8) Experimental value; (9) Theoretical value; (10) Deviation, %.

1.2. Calculation of Dielectric Loss Angle Tangent for Glass Fibre Reinforced Plastic

For capacitors with dielectric qualities, the positional variational deviation for voltage and current is no longer 90°, but is an acute angle φ; the complement of angle φ, angle δ, is the dielectric loss angle. Based on the current power formula, it is possible to derive the formula for calculating the dielectric loss angle tangent for unidirectional glass fibre reinforced plastic along the direction of the fibres; the formula is:

$$\mathrm{tg}\,\delta_{\parallel} = \frac{V_f\varepsilon_f\,\mathrm{tg}\,\delta_f + (1-V_f-V_0)\varepsilon_m\,\mathrm{tg}\,\delta_m + V_0\varepsilon_0\,\mathrm{tg}\,\delta_0}{V_f\varepsilon_f + (1-V_f-V_0)\varepsilon_m + V_0\varepsilon_0}. \tag{8}$$

Concerning the crosswise direction of unidirectional glass fibre reinforced plastic, or the vertical direction of bidirectional glass fibre reinforced plastic, it is possible to derive the formula for theoretical calculation of the dielectric loss angle tangent:

$$\mathrm{tg}\,\delta_{\perp} = \{[V_f\varepsilon_m\varepsilon_0\,\mathrm{tg}\,\delta_f + (1-V_f-V_0)\varepsilon_f\varepsilon_0\,\mathrm{tg}\,\delta_m + V_0\varepsilon_f\varepsilon_m\,\mathrm{tg}\,\delta_0]\varepsilon\}/\{\varepsilon_f\varepsilon_m\varepsilon_0\}. \tag{9}$$

For bidirectional glass fibre reinforced plastic, the formulas for calculating the dielectric loss angle tangent along the warp and the weft are:

$$\left.\begin{aligned} \mathrm{tg}\,\delta_L &= \left(\frac{n_L}{n_L+n_T}\varepsilon_{\parallel}\,\mathrm{tg}\,\delta_{\parallel} + \frac{n_T}{n_L+n_T}\varepsilon_{\perp}\,\mathrm{tg}\,\delta_{\perp}\right)\Big/\varepsilon_L,\\ \mathrm{tg}\,\delta_T &= \left(\frac{n_L}{n_L+n_T}\varepsilon_{\perp}\,\mathrm{tg}\,\delta_{\perp} + \frac{n_T}{n_L+n_T}\varepsilon_{\parallel}\,\mathrm{tg}\,\delta_{\parallel}\right)\Big/\varepsilon_T. \end{aligned}\right\} \tag{10}$$

The dielectric loss angle tangent for the crosswise direction for unidirectional glass fibre reinforced plastic and the vertical direction for bidirectional glass fibre reinforced plastic is related to the fibre content as shown in Fig. 3. For calculation, the values of ε_f and ε_m are the same as before, $tg\delta_f=0.004$, and $tg\delta_m=0.015$.

Experimental and calculated values for the dielectric loss angle tangent of some glass fibre reinforced plastics are compared in Table 3.

2. The High-frequency Dielectric Property of Glass Fibre Reinforced Plastic and Honeycomb Layers

Honeycomb layers are a material with many holes, as shown in Fig. 4. Based on the principle behind composite electric capacitors, it is theoretically possible to derive the dielectric property of the honeycomb layer.

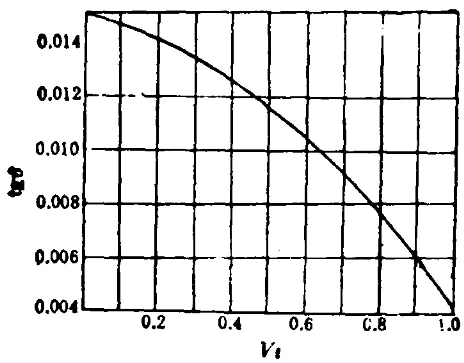


Fig. 3. Relation of dielectric loss angle tangent for crosswise (unidirectional fibres) or vertical (bidirectional fibres) direction with fibre content.

Table 3. Comparison Between Calculated and Theoretical Values for the Dielectric Loss Angle Tangent for Glass Fibre Reinforced Plastics

(1) 性能 \ (2) 材料		(3) DAP 玻璃钢	(4) 酚醛-环氧玻璃钢	(5) 聚酯玻璃钢
(6) 树脂含量 A(%)		48	30	50
(7) 介电损耗角正切 tgδ	(8) 测试值	0.0111	0.014—0.017	0.023—0.025
	(9) 理论值	0.0125	0.0168	0.022*
	(10) 误差(%)	−12.6	−20.0—1.2	4.3—12.0

*For calculations, $tg\delta_{-}=0.026$.

Key: (1) Property; (2) Material; (3) DAP glass fibre reinforced plastic; (4) Phenolic/epoxy glass fibre reinforced plastic; (5) Polyester glass fibre reinforced plastic; (6) Resin content A, %; (7) Dielectric loss angle tangent tgδ; (8) Experimental value; (9) Theoretical value; (10) Deviation, %.

2.1. Dielectric Constant for Honeycomb Layers

The formula for the theoretical calculation of the dielectic constant for honeycomb layers is:

$$\varepsilon_c = V_s\varepsilon_s + (1 - V_s)\varepsilon_0 \quad (11)$$

In the formula, ε_s is the dielectric constant for the material in the honeycomb wall, and V_s is defined as:

$$V_s = \frac{d/c + 1}{(d/c + \cos\theta)(\sin\theta + 2t_s/c)}(t_s/c) \tag{12}$$

in which d, c, θ, and t_s are as shown on Fig. 4.

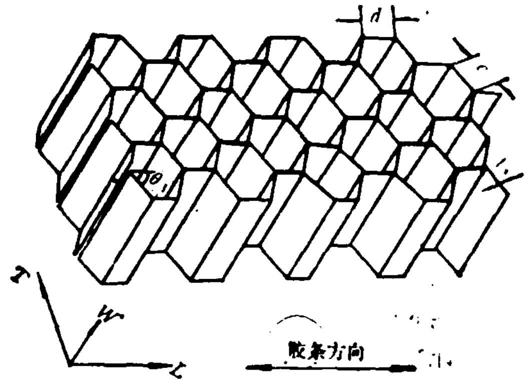


Fig. 4. Structure of honeycomb layer. Key: (1) Glue strip direction.

The relationship of the honeycomb layer dielectric constant with the honeycomb cell side length c and the resin content (for a regular hexagon honeycomb) is shown in Fig. 5. A comparison between experimental and calculated values is given in Table 4.

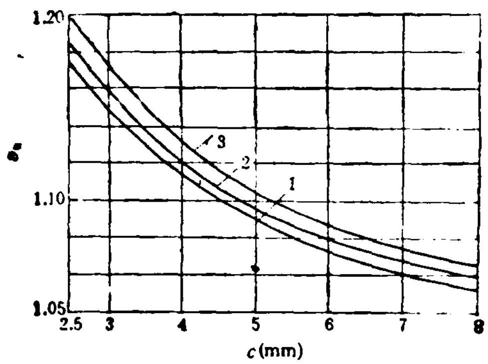


Fig. 5. Relation of dielectrical constant of honeycomb layer with honeycomb cell side length and resin content.
1. A=40%; 2. A=45%; 3. A=50%.

2.2 Dielectric Loss Angle Tangent of Honeycomb Layer

The formula for the theoretical calculation of the dielectric loss angle tangent of the honeycomb layer is:

$$\mathrm{tg}\,\delta_c = \frac{V_s\varepsilon_s\,\mathrm{tg}\,\delta_s + (1 - V_s)\varepsilon_0\,\mathrm{tg}\,\delta_0}{V_s\varepsilon_s + (1 - V_s)\varepsilon_0} \tag{13}$$

In the formula, $\mathrm{tg}\delta_c$ is the dielectric loss angle tangent for the honeycomb wall material along the fibre direction. $\mathrm{tg}\delta_0$ is the dielectric loss angle tangent of the air or gas in the cell.

For the relation between the dielectric loss angle tangent of the honeycomb layer and the length of honeycomb cell side c, refer to Fig. 6. Table 4 shows the comparison between experimental and calculated values. For calculations, the value for ε_f, ε_m, $\mathrm{tg}\delta_f$ and $\mathrm{tg}\delta_m$ are the same as before; for dry air ε=1 and $\mathrm{tg}\delta$=0. Because the honeycomb wall is single-layer glass fibre

reinforced plastic, it contains a certain water content; based on experimental results, the water content is 0.13% to 0.24% of the fabric weight. The value for ε_w is 81, that for $tg\delta_w$ is 0.55.

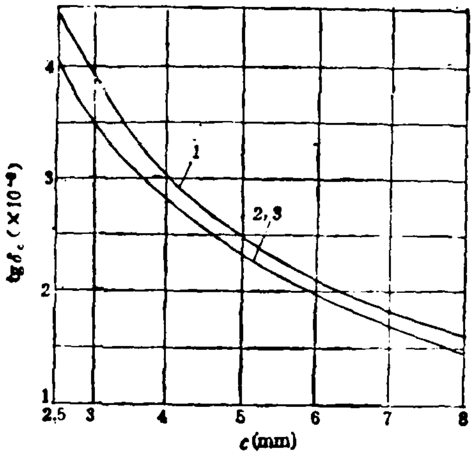


Fig. 6. Relation of dielectric loss angle tangent of honeycomb layer with cell wall length and resin content.
1. A=40%; 2. A=45%; 3. A=50%.

Table 4. Comparison of Experimental and Calculated Values for Honeycomb Layer Dielectric Properties

性 能 (2) \ (1) 蜂格边长 c(mm)		2.5	2.7	3	4
(3) 树脂含量 A(%)		40.5	43.8	44.3	45.0
(4) 密度 ρ_c(kg/m³)		98.9	94.5	93.9	69.6
ε_c	(5) 测试值	1.133	1.153	1.130	1.107
	(6) 理论值	1.17	1.17	1.15	1.119
	(7) 误差(%)	3.3	1.5	1.2	1.1
$tg\delta_c$ ($\times 10^{-3}$)	(5) 测试值	3.59	4.49	3.51	2.68
	(6) 理论值	4.38	4.15	3.54	2.80
	(7) 误差(%)	−22.0	7.6	−0.9	−4.5

Key: (1) Honeycomb cell wall length *c* (mm); (2) Property; (3) Resin content A, %; (4) Density ρ_c (kg/m³); (5) Experimental value; (6) Calculated value; (7) Deviation, %.

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